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METHOD OF DETERMINATION OF ION TEMPERATURE BY THE VARIATIONS OF SATELLITE INDUCED ION TRAP CURRENTS AND ESTIMATE OF THE UPPER LIMIT OF ION TEMPERATURE AT ALTITUDES OF 10000 KILOMETERS AND HIGHER ACCORDING TO DATA OF AES "ELEKTRON-2"

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SUMMARY

It is shown that measurements of collector current variations of an ion trap with zero potential at outer grid, installed aboard a spinning spacecraft flying within the ionosphere, may be utilized for the determination of ion temperature T_i.

The estimates of the upper limit of T_i made after the data of the ion trap installed aboard AES "ELEKTRON-2" have shown that in the altitude range 4000 – 8000 km the temperature of ions did not exceed 10,000° K.

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As far as we know the first rough estimate of ion temperature at altitudes of the order of several thousand kilometers was made in the work [1] according to data of charged particle traps installed aboard spacecraft "LUNA-2" launched in 1959. The outer grids of four traps on LUNA-2 had the following potentials relative to craft's frame: – 10 v, – 5 v and +15 v. Experiment has shown that the positive collector currents registered in traps at altitudes to ~ 20,000 km depend essentially on comparatively small differences in potentials of traps' outer grids having taken place, whereas in the trap with outer grid potential of +15 v no positive currents were generally registered at altitudes above 3000 km. This is evidence of comparatively low energies of positive ions in the altitude region considered, and it allowed the authors of [1] to estimate the value of T_i in that region as not exceeding some 10,000°K.

Note that in essence simultaneous measurements with the aid of four traps with different outer grid potentials are equivalent to obtaining of four points on the sonde volt-ampere characteristic.

(*) SPOSOB OPREDELENIYA IONNOY TEMPERATURY PO IZMENENIYAM TOKA IONNOY LOVUSHKI, VYZVANNYM VRASHCHENIYEM SPUTNIKA, I OTSENKA VERKHNEGO PREDELA IONNOY TEMPERATURY NA VYSOTAKH $\gtrsim$ 10,000 KM PO DANNYK "ELEKTRONA-2"

There exists still another possibility of estimating T_i, and namely, by the variations of collector current of a trap with zero potential in the outer grid and a flat collector installed on a spinning spacecraft ("LUNA-2" and "ELEKTRON-2" were such spacecrafts in particular).

For an arbitrary position of the trap relative to the axis (or axes) of rotation of the spacecraft the position of the normal to trap's collector relative to the "translational" velocity vector of the device (i.e. its velocity along the trajectory $v_{к.а.}$) must vary periodically, which must, in its turn, induce corresponding periodic variations ("modulation") of the registered collector current. Such a modulation of collector currents was indeed observed during the passage through the plasma sheath of the Earth on both "LUNA-2" and on each convolution of AES "ELEKTRON-2" launched in 1964, on which there was also installed a charged particle trap with zero potential in the outer grid [2]. If we considered that the maximum values of collector current of such a trap correspond to overlappings of the normal to collector current with spacecraft's velocity vector, and the minimum values – to the location of the trap in the ion shadow, at which the direction of the normal to collector is opposite to velocity vector, we might determine the upper threshold of T_i by the ratio of these values.

Let us now show how this is done. Assume that:

1) the distribution of charged particles by velocities in the ionosphere is Maxwellian, and the influence of the electric field induced by spacecraft's potential difference from that of the plasma surrounding it can be neglected;

2) the spacecraft spins around an axis perpendicular to the nromal to trap's collector current; the spacecraft's "translational" velocity vector lies in a plane perpendicular to the indicated rotation axis;

3) the registration of collector current is practically realized continuously (that is, there is a continuous current registration).

Note that in reality conditions 2) and 3) are usually not fulfilled. This is why we shall examine how T_i can be determined in the case of fulfillment of these conditions, and then we shall estimate how the nonfulfillment of these conditions affects the result.

We shall make use of a system of coordinates with origin at the mass center of the spacecraft, and the axis z coinciding with the spacecraft's translational velocity vector.

Then the magnitude of the maximum trap's collector current will be determined from the expression

$$I_{\text{к}\,\max} = eS \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{0} c_z f(\mathbf{c})\, d^3\mathbf{c}, \tag{1}$$

and that of current minimum by

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$$I_{\kappa\,\min} = eS \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{0}^{\infty} c_z f(\mathbf{c})\, d^3\mathbf{c}, \qquad (2)$$

where $\underline{e}$ is the charge of the electron, S is the are of trap's collector, $\vec{c} = \vec{v} - \mathbf{v}_{\kappa.a.}$ is the velocity of ions in the selected system of coordinates, $\vec{v}$ is the thermal velocity of ions and $f(\vec{c})$ is the distribution function.

In accord with the earlier said we shall take for f(v) a Maxwellian distribution function; then

$$f(c) = n_i \left(\frac{m_i}{2\pi k T_i}\right)^{3/2} \exp\left\{-\frac{m_i}{2kT_i}\left[v_x^2 + v_y^2 + (c_z + v_{\kappa.a.})^2\right]\right\},$$

in which the temperature T_i corresponds to that of an ionosphere unperturbed by the spacecraft (since we neglected the satellite's potential).

Integrating (1) and (2) and assuming that the concentration of ions n_i at times of measurement of maximum and minimum currents are identical, we obtain for the ratio of currents the following expression

$$\frac{I_{\kappa\,\max}}{I_{\kappa\,\min}} = \frac{x\Phi(x\sqrt{2}) + \frac{1}{\sqrt{\pi}}e^{-x^2} + x}{x\Phi(x\sqrt{2}) + \frac{1}{\sqrt{\pi}}e^{-x^2} - x}, \qquad (3)$$

here $x = (mv^2_{\kappa.a.}/2kT_i)^{1/2}$, m is the mass of the proton, and $\Phi(x\sqrt{2})$ is the function of errors. It may be seen from formula (3) that the ratio $I_{\kappa\,\max}/I_{\kappa\,\min}$ depends for a known $v_{\kappa.a.}$ only on T_i; thus if we construct the dependence of $I_{\kappa\,\max}/I_{\kappa\,\min}$ on $\underline{x}$ or on $T_i = mv^2_{\kappa.a.}/2kx^2$, we may take advantage of the graph obtained for the determination of T_i. Obviously, as $x \to 0$, i.e. at very high temperatures $I_{\kappa\,\max}/I_{\kappa\,\min} \to 1$, and for $x \gg 1$, $(I_{\kappa\,\max}/I_{\kappa\,\min} = (1/\pi\sqrt{\pi})x^3e^{x^2}$ for $x \gg 1)$ this ratio becomes extremely great.

Part of the graph of $I_{\kappa\,\max}/I_{\kappa\,\min} = F(x)$ dependence for values of $\underline{x}$ in the range $0.1 < x < 1.5$ is given in Fig.1. T_i are computed for $v_{\kappa.a.} = 8$ км/sec.

As already noted, we dispose of the results of measurements of I_k conducted in the peripheral region of the Earth's ionosphere (to which we refer the altitudes up to 10 to 20 thousand km) with the help of a charged particle trap on ELEKTRON-2. For the sake of an example we brought out in Figs 2 and 3 the results of measurements of I_k for two passages of ELEKTRON-2 near the Earth. Analogous results were obtained on spacecraft "LUNA-2" (see Fig.3 of ref. [1]). For the estimate of the ion temperature we shall take advantage only of points at altitudes < 10,000 km (marked by triangles). It may be seen from Figs 2 and 3 that if one determines the ratio $I_{\kappa\,\max}/I_{\kappa\,\min}$ for the consecutive extreme points similar to those noted, so that the first one with a low value of I_k correspond to lower altitude and the second – with great value of I_k – be related to greater height, this value will constitute a magnitude of the order of 10.

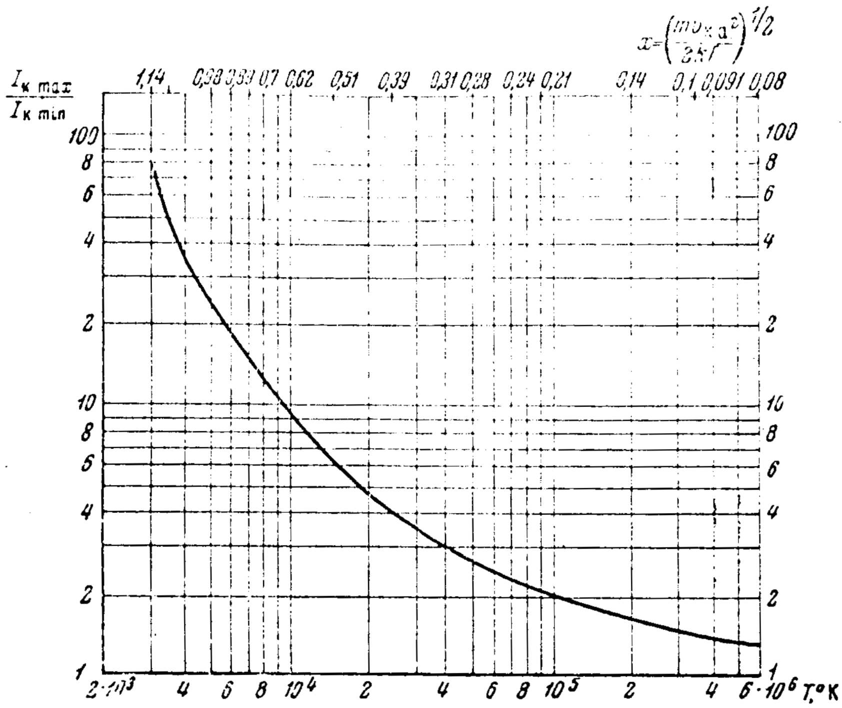

Fig.1 Dependence of the maximum and minimum collector current ratios of a trap with zero potential at outer grid, corresponding to periodical variations of trap's position on account of spacecraft spinning, on the quantity $x = \sqrt{mv_{\text{к.а.}}/2kT_i}$ [see formula (3)]

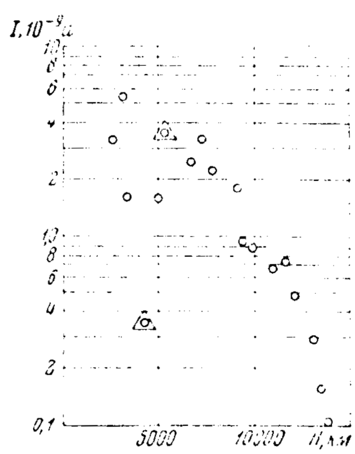

Fig.2. Values of collector currents of the trap installed on ELEKTRON-2, correspodding to its passage near the Earth on 30 January 1964 between the hours 1008 and 1120 U.T.

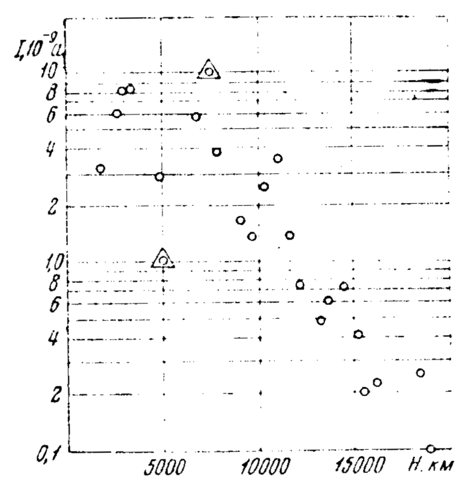

Fig.3. Values of the collector currents of the trap installed on ELEKTRON-2, corresponding to its passage near the Earth on 31 Jan. 1964 from 0846 to 0952 hours U.T.

However, we may not utilize the data of Figures 2 and 3 for the determination of T_i without estimating the degree of fulfillment of conditions during the experiment in the assumption of which the graph of Fig.1 was plotted.

Let us examine in sequence how each of the admitted assumptions affects the determination of T_i by the method indicated.

Assumption (1) allowed us to consider that the temperature determined by the proposed method corresponds to the temperature of the ionosphere unperturbed by the spacecraft, inasmuch as its potential is near zero.

In our case such an assumption can be substantiated as follows. Data on maximum ionic currents registered with the aid of the charged particle traps aboard ELEKTRON-2 are compiled in [2]; they correspond all to same altitudes ($H \leqslant 10000$ km) with satellite location in the cone of Earth's shadow and in the region illuminated by the Sun. In nighttime conditions the satellite potenital must be negative while in Sun's illumination it may change sign. This circumstance should be reflecting upon current magnitude. The proximity of current values registered in both cases points to the smallness of the satellite potential relative to the surrounding medium of this altitude region. The conclusion relative to the smallness of satellite potential in the altitude region under consideration by us was also derived in the work by Serbu, describing the results obtained on the station "IMP-1" [3]. This is why the utilization of Maxwellian distribution corresponding to $T = T_i$ at altitudes considered should be considered as justified. Note, incidently, that the Maxwellian distribution is precisely the one assumed in numerous analogous calculations of ion velocity distribution in the ionosphere (beginning with Whipple's work [4]).

There is no basis to consider that in measurement conditions on ELEKTRON-2 assumption (2) was fulfilled, as no precise data were available to us on the orientation of the normal to trap's collector relative to velocity vector. This might have led to the fact that in process of modulation on account of spacecraft spinning the maximum values $I_{k\ max}$ were found to be less than what ought to have taken place in case of coincidence of the normal to collector with the satellite's translation velocity vector, the minimum values $I_{k\ min}$ being correspondingly overrated. At the same time the ratio $I_{k\ max}/I_{k\ min}$ may be below the "real" (obtained from Fig.1), while the value of T_i may result to be overrated.

Finally, the conditions of measurement on ELEKTRON-2 did not correspond to assumption (3) either. The registration of I_k at altitudes considered was not conducted uninterruptedly, but only once in two minutes. At the same time the indicated interval between two consecutive measurements was by order of magnitude close to satellite's rotation period relative to its center of masses. As a consequence of this the results of measurements plotted in Figs 2 and 3, reflect, because of spacecraft's rotation, not the authentic measurements of I_k but a certain "quasistroboscopic" pattern. If at the same time we choose fot $I_{k\ min}$ and $I_{k\ max}$ the pairs of extreme points, following one another and outlined in Fig.3 by triangles, we find that :

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a) firstly, the quantity $I_{k\ min}$ may be overrated, for it is not excluded that the measurement was conducted at the moment of time when the value of I_k was not the least;

b) secondly, the quantity $I_{k\ max}$ may underrated, since measurement may have been conducted not at the moment of time when the value of I_k was greatest;

c) thirdly, it was assumed that the concentration of ions at time of measurements of $I_{k\ max}$ and $I_{k\ min}$ was equal; in reality, concentration drops with altitude increase, while the points at which $I_{k\ max}$ and $I_{k\ min}$ were measured at two minute interval, are found to be significantly spatially scattered; thus, by selecting a point with $I_{k\ max}$ at greater height than with $I_{k\ min}$, we obviously lower the ratio $I_{k\ max}/\ I_{k\ min}$.

Therefore, scarce measurements of I_k can only lead to lowering the ratio $I_{k\ max}/\ I_{k\ min}$ by comparison with the true value, i. e. to the overrating of the value of T_i sought for.

It follows from the above-said that the nonfulfillment of each of the indicated conditions (2), (3), may affect the value of T_i being determined in one and the same direction, overrating it by comparison with the real value. This is why T_i determined from the ratios $I_{k\ max}/\ I_{k\ min}$, corresponding to points similar to those which are outlined by triangles in Figs 2 and 3, must be considered as the upper threshold (limit) of possible values of T_i in the altitude range considered.

In the present paper we limited ourselves to the estimate of the value of T_i according to measurements plotted in Figures 2 and 3. Note that in the altitude region < 10000 km these data refer to the earlier mentioned cases of ELEKTRON-2's location in the cone of Earth's shadow, when the satellite's potential is knowingly negative, while the values of the collector current are entirely free from the influence of photoemission.

It may be seen from Fig.2 that the ratio $I_{k\ max}\ /\ I_{k\ min}$, determined by the points marked by triangles, may characterize T_i in the 4000 – 5200 km altitude range, while the corresponding altitude interval in the case of Fig.3 is 5200 – 7800 km. The satellite velocity in the former was $\sim$ 8 km/sec and in the latter $\sim$ 7 km/sec.

In either case $I_{k\ max}\ /\ I_{k\ min} = 10$. Then, according to the graph of Fig.1, for 30 January 1964 the upper limit of T_i is 9000 – 10000°K. For 31 January 1964 the value of T_i estimated analogously was $\sim$ 7000°K. Therefore, these estimates of the temperature of ions allow us to refine (lower) the previous values for the indicated altitudes of the upper limit of temperature given in [1] for the entire peripheral region of the Earth's plasma sheath.

The Anderson, Bennett and Hale's work was published in 1965 [5]. In it the results are described of the interpretation of data obtained with the aid of the ion trap installed on a rocket launched to 5500 km in October 1960. The authors admit at the same time that in the 4000 – 5200 km altitude range the ion temperature exceeded 32000°K. The estimates presented above are opposed to such a possibility.

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